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Thermographic Inspection of Tank-Car Insulation: Field Test Manual

for

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by

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16. Abstract

An inspection technique was developed to find thermal insulation deficiencies on rail tank-cars. Using a thermal imager to locate insulation gaps under the tank steel jacket, this method relies on a small temperature difference between the tank lading and the surroundings. Solar heating can also assist in generating thermal gradients that the thermal imager can identify. Further details of this system can be found in the 1998 Transportation Development Centre report entitled *Thermographic Inspection of Tank-Car Thermal Insulation*, TP 13203E.

This document is intended to serve as a field manual for inspectors using thermal imagers to detect thermal insulation deficiencies on rail tank-cars. Its scope is limited to the description of:

- basic methodology
- equipment/software operation
- inspection procedure
- image interpretation
- insulation defect assessment

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16. Résumé

Une technique d'inspection a été mise au point pour repérer les défauts d'isolation thermique des wagons-citernes. Elle fait appel à un imageur thermique qui situe ces défauts sous la jaquette en acier de la citerne à partir des légères différences de température détectées entre le contenu de la citerne et le milieu ambiant. Il a été également établi que les conditions ensoleillées sont de nature à engendrer des gradients thermiques détectables par l'imageur thermique. On trouvera plus de détails sur cet appareil dans le rapport TP 13203E intitulé *Thermographic Inspection of Tank-Car Thermal Insulation*, fait pour le Centre de développement des transports en 1998.

Ce document est destiné à guider les inspecteurs dans l'emploi d'un imageur thermique pour détecter les défauts d'isolation thermique des wagons-citernes. Il comprend seulement une description :

- de la méthodologie de base
- du fonctionnement de l'appareil et du logiciel associé
- de la procédure d'inspection
- de l'interprétation des images
- de l'évaluation des défauts d'isolation

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Summary

This document is intended to serve as a field manual for inspectors using thermal imagers to detect thermal insulation deficiencies on rail tank-cars.

The document describes:

- basic methodology
- equipment/software operation
- inspection procedure
- image interpretation
- insulation defect assessment

The technology described in this manual can also be used to assist emergency response teams in recognizing other tank car features, such as:

- liquid levels in tanks
- hot spots (overheated bearings, etc.)
- leaks (local cooled spots due to liquid flashing)

A thermal imager can be used to locate thermal insulation deficiencies on a tank when a thermal gradient is present. This technique can be used with both thermally insulated and thermally protected tanks, and applies to a wide range of insulation types.

Small thermal gradients are caused by natural day-night heating-cooling cycles. Large thermal gradients may be present during filling or off-loading of tanks or under solar heated conditions. Inspection can be performed on empty tanks by using heat injection (steam or hot air) techniques.

The results for large thermal gradient testing are easy to interpret, that is, deficiencies will be obvious. In the case of small thermal gradients, care must be taken to ensure that indications of thermal deficiencies are real and not simply reflection effects, solar effects, or surface finish effects.

Insulation defects in thermal protection systems reduce the survivability of tanks in fires. The risk of tank failure in a fire increases with the size of deficiencies and the shape and location. Survivability of a tank with deficiencies depends on a number of factors, including:

- initial fill
- PRV operating characteristics
- insulation condition and properties
- location, shape, and size of defects

Simulation results suggest that a thermal protection system with a less than 4 percent defect has a good probability of surviving a pool fire for 100 minutes (as per CGSB standard). Larger deficiencies may also be acceptable, but come with an increased risk of tank failure in a fire.

Deficiencies in thermal insulation systems increase heat transfer between the tank lading and the surroundings. Systems consisting of 51 mm of fibreglass and 51 mm of ceramic blanket cannot have significant deficiencies and pass the current CGSB standard for thermal insulation systems.

The proposed pass/fail criteria for defective thermal protection are based on the analysis reported by Birk and Cunningham (Transportation Development Centre report, *Thermographic Inspection of Tank-Car Thermal Insulation*, TP 13203E, 1998). This analysis has not been fully validated and therefore allowing any defect has risk associated with it.

The assessment procedure presented in this manual is preliminary and should be used with extreme caution. Testing is needed to verify the appropriateness of the stated defect percentages. The authors of this report do not guarantee that the stated defect percentages are safe in a real-world accident.

Sommaire

Ce document est destiné à guider les inspecteurs dans l’emploi d’un imageur thermique pour détecter les défauts d’isolation thermique des wagons-citernes.

Il décrit :

- la méthodologie de base
- le fonctionnement de l’appareil et du logiciel associé
- la procédure d’inspection
- l’interprétation des images
- l’évaluation des défauts d’isolation

La technologie décrite dans ce guide peut aussi aider les équipes d’intervention d’urgence à déterminer d’autres caractéristiques des wagons-citernes telles que :

- le niveau de remplissage
- les points chauds (surchauffe des boîtes d’essieu, etc.)
- les fuites (zones de refroidissement localisé par vaporisation instantanée de la cargaison liquide)

Un imageur thermique peut servir à cerner les défauts d’isolation d’un wagon-citerne par détection d’un gradient thermique. Cette technique est utile aussi bien dans le cas des wagons-citernes à protection thermique que dans celui des wagons-citernes isothermes et elle vaut pour une large gamme d’isolants thermiques.

Les cycles de réchauffement diurne-refroidissement nocturne donnent lieu à de petits gradients thermiques. Le remplissage ou la vidange des citernes peut engendrer d’importants gradients thermiques tout comme un rayonnement solaire intense. L’inspection des wagons-citernes vides se fera après injection préalable de vapeur ou d’air chaud.

L’imagerie thermique des citernes présentant un gradient thermique prononcé est facile à interpréter. Bref, les défauts y apparaissent clairement. À l’interprétation des images de citernes à faible gradient thermique, il faut s’assurer que les indices de défaut d’isolation ne sont pas en fait des effets de réflexion, d’échauffement solaire ou attribuables à l’état de surface de la citerne.

Les défauts d’isolation des systèmes de protection thermique ont pour effet de réduire la survivabilité des wagons-citernes dans un incendie. Le risque de rupture de la citerne croît avec l’étendue des défauts d’isolation et selon leur forme et emplacement. Elle dépend aussi d’autres facteurs, notamment :

- le niveau de remplissage initial
- les caractéristiques de fonctionnement des soupapes de sûreté

- l’état et les propriétés de l’isolant
- l’emplacement, la forme et l’étendue des défauts

D’après les résultats de la simulation, un système de protection thermique défectueux à moins de 4 pour cent a de bonnes chances de résister aux effets d’un bain de flammes enveloppantes pendant 100 minutes (comme l’exige la norme ONGC). Des défauts plus étendus peuvent aussi être admissibles, mais au prix d’un risque de rupture accru en cas d’incendie.

Les défauts d’isolation des wagons-citernes ont pour effet d’accroître les transferts thermiques entre la cargaison et le milieu ambiant. Les systèmes de protection thermique formés d’une couche de fibre de verre de 51 mm d’épaisseur et d’une doublure céramique de même épaisseur ne pourront satisfaire aux critères actuels d’isolation thermique de la norme ONGC applicable s’ils présentent des défauts étendus.

Les critères proposés de réussite/échec aux essais sont fondés sur les résultats de l’analyse présentée par Birk et Cunningham dans le rapport TP 13203E *Thermographic Inspection of Tank-Car Thermal Insulation*, 1998, fait pour le Centre de développement des transports. Cette analyse n’ayant pas été entièrement validée, l’acceptation d’un wagon-citerne présentant un défaut d’isolation quel qu’il soit comporte des risques.

La méthode d’évaluation proposée est préliminaire et devrait donc être appliquée avec énormément de circonspection. Il faut encore valider par des essais pratiques les pourcentages de défaut d’isolation avancés. Les auteurs du rapport ne peuvent garantir la survivabilité à un accident d’un wagon-citerne présentant un défaut d’isolation de l’étendue indiquée.

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1. Introduction

This document is intended as a field manual for inspectors using thermal imagers to detect thermal insulation deficiencies on rail tank-cars

1.1 Objectives

The primary objective of this document is to present techniques for the use of thermal imagers to detect thermal insulation deficiencies in thermally protected or thermally insulated rail tank-cars.

1.2 Scope

The scope of this manual is limited to the description of:

- basic methodology
- equipment/software operation
- inspection procedure
- image interpretation
- insulation defect assessment

This manual is not a reference manual for thermal radiation physics.

Readers should be aware that the technology described in this manual can assist emergency response teams in recognizing other accident features such as:

- liquid levels in tanks
- hot spots (overheated bearings, etc.)
- leaks (local cooled spots due to liquid flashing)

2. Method

2.1 Overview of Thermography

Thermography is a method similar to photography, except that the "picture" taken is not of visible light, but of thermal radiation. Visible light and thermal radiation are forms of electromagnetic radiation. In this application we limit our interest to thermal radiation falling in the 3-5 μm or 8-14 μm wavebands of the electromagnetic spectrum. This is because the available thermal imaging cameras fall in these wavebands. Infrared (IR) cameras use these wavebands because the atmosphere does not interfere (i.e. absorb radiation) strongly in these wavebands.

This document cannot take the place of basic education in thermal radiation physics. If readers have no background in this area is it is highly recommended that they obtain some training. Organizations offer specific thermography training (for example, Academy of Infrared Thermography, 2955 Westsyde Road, Kamloops, BC, V2B 7E7).

An object emits thermal radiation when it has a temperature above 0 K (-273^{o}C). Therefore, all objects we know emit thermal radiation. Low temperature objects radiate more in the 8-14 μm waveband and hot objects radiate more in the 3-5 μm waveband. For example, the sun radiates more in the 3-5 μm band than in the 8-14 μm band. Surfaces also reflect thermal radiation from surrounding objects such as the ground, sky, sun and other nearby structures. When viewing an object using a thermal imager the viewer will see both emitted and reflected radiation.

The temperature of an object depends on many factors, such as internal heat sources, internal and external convection and thermal radiation. An object sitting in the sun will heat up because of solar radiation. An object will cool down at night because of heat loss through convection and radiation.

In this specific application, i.e. inspection of thermal insulation deficiencies, the method of thermographic inspection relies on the fact that the object to be inspected has temperature variations on its surface that are caused by variation in thermal insulation. In this case the thermal gradients are caused by high or low lading temperatures relative to ambient or external radiation from the sun or to the cool sky. These temperature differences may be due to the filling or unloading temperatures used for a specific commodity or the natural day/night or seasonal temperature fluctuations.

2.2 Terminology

The fields of thermography and image processing have a specialized terminology. The following limited list of terms should be adequate for this application.

Radiation Terminology

absorptivity	a measure of how well a body absorbs thermal radiation (ranges from 0 to 1, usually absorptivity = emissivity)
diffuse	when a surface reflects or emits radiation equally in all directions
electromagnetic spectrum	thermal radiation falls in the range of 0.1 to 1000 µm in the electromagnetic spectrum. Visible light falls in the range from 0.35 to 0.75 µm. Hot objects radiate more at smaller wavelengths. That is why you can see very hot objects radiate. The sun radiates very strongly at short wavelengths.
emissivity	a measure of how strongly a surface emits thermal radiation (emissivity = 1 for a black body or perfect radiator, emissivity = 0 for a perfect reflector)
radiance	radiation leaving a surface per unit area of surface, per unit solid angle
radiosity	total radiation power leaving a surface per unit area of surface (radiosity = emitted + reflected radiation)
reflectivity	a measure of how well a surface reflects thermal radiation (reflectivity = 1- absorptivity)
spectral properties	absorptivity, emissivity and reflectivity all vary with spectral wavelength. Therefore, surfaces will absorb solar radiation differently than longwave radiation. For example, white paint reflects solar radiation, but black surfaces absorb solar radiation. Therefore, black surfaces get hot in the sun while white surfaces will stay cool. Black and white surfaces absorb and reflect longwave radiation to about the same degree.
specular	when an object reflects like a mirror

Image Processing Terminology

contrast	Degree of difference between the shades of adjacent objects in an image.
frame grabber	An internal or external computer card that accepts a video signal (from a VCR or video camera) and can be used to capture or

	“grab” single or multiple video frames. These frames can then be stored on the computer for later analysis, printing, etc.
grey scale image	An image made up a number of pixels, with each pixel having a shade of grey ranging from black to white. The number of shades of grey is typically 256 (i.e. 8 bit). Each shade of grey is assigned a number referred to as the shade’s “grey scale”. Generally white is assigned 255 and black 0 (or 15).
histogram stretch	An image processing technique that re-maps a narrow range of grey scale over the full range. Any grey scales outside of this range are made either black or white depending on whether they are below or above the selected range.
TIFF	Tagged image file format - a specific type of computer graphics file widely compatible with most image analysis software.

2.3 Thermal Imaging Technologies

Commerical thermal imagers are available from various manufacturers. Modern imagers look very much like home video cameras. They have the following common features of video cameras:

- point and shoot
- they need a battery or a source of power
- they need to be focused on the subject
- they need to be held steady
- they require certain conditions to give good pictures (video cameras need visible light, thermal imager needs temperature gradients)
- they have a lens with a fixed or adjustable field of view and focal length.
- they record images to video tape or some can capture frames like a still digital camera.

A thermal imager has two adjustments that are a little different those of a video camera – span and level. The level is the lowest temperature that can be viewed, and the span (or gain) is the range between the lowest and highest temperature that can be viewed. Most modern cameras have an automatic setting for these adjustments. However, sometimes the automatic setting is not appropriate and an inspector will want to go on manual to view specific features on a subject.

Industrial imagers generally operate in parts of the electromagnetic spectrum (wavebands) that are not strongly affected by the atmosphere. The most common wavebands are two atmospheric windows at 3-5 μm and 8-12 μm. Cameras that operate in either of these wavebands could be used for tank inspection.

Modern thermal imaging cameras are relatively easy to operate and are capable of resolving temperature differences in the order of 0.05 to 0.5°C, more than adequate for this application. However, inspectors should be aware that external effects and tank surface finish can add “clutter” to images that represent temperature variations on the order of 2°C or more and therefore image interpretation may be more difficult. This will be discussed further later in this report.

2.4 Infrared Thermal Image

For a given thermal imager, the image obtained will be a function of the following:

- temperature of object
- surface finish of object
- view angle to the object surface
- other sources of radiation including the background (i.e. ground, sky, solar, etc.)

The following sections discuss each of these important factors.

Temperature

The temperature of an object should be different from its surroundings for it to be effectively resolved from the background. The larger the temperature difference, the easier it will be to resolve the object. Current thermal imagers can resolve temperature differences of less than 0.5°C.

Surface Finish

Most tank-cars are painted black or white. This paint may be new and glossy or old and flat. They may be rusty, dirty and some may have patches of new paint with patches of old. This means that surface radiative properties will vary, which, in turn, will cause a variation in the image.

It should be noted that white paint and black paint look almost the same in the 3-5 and 8-14 μm wavebands. However, they absorb and reflect solar radiation very differently and this affects surface temperature and thermal image very strongly. A white surface reflects most of the solar radiation whereas the black surface absorbs most. This is why black surfaces get much hotter in the sun than white surfaces.

Wet surfaces also reflect differently than dry surfaces. Therefore, rain has two effects on a surface -- it will cause a cooling or warming effect, which will change temperatures and change the way the surface reflects its surroundings.

View Angle

The view angle is important because it affects the viewed image. If an imager is pointed at a curved surface (such as a rail tank-car or tank truck) it will see a variation in surface radiance due to the effect of angle. A painted surface becomes more reflective as the view angle becomes more oblique. Therefore, if a tank is viewed from the side, the top of the tank will look different from the side due to view angle differences.

Other Radiation Sources

Other sources of radiation will be reflected off the surface. If the tank is sitting in the sun then expect the sun to strongly influence the viewed image. This is due to both solar heating and reflection.

If there are nearby objects that radiate strongly (cold or hot) then you may see their reflection in the tank surface. Examples of these kinds of sources are:

- flames
- hot pipes, vessels
- smoke stacks and plumes
- welders
- snow, ice

2.5 Thermography of Tank-Cars and Tank Trucks

The thermography of tanks involves viewing the tank from the side or top using a thermal imaging camera. The images taken by the camera can be stored on video tape for later analysis or they can be captured to a computer for analysis and printing.

Depending on the camera optics, and the position of the camera it may be possible to view the entire tank side in one field of view (FOV). In this case it is relatively easy to keep a clear record of what the inspector has viewed. If space is limited between tanks then the camera may have to be placed close to the tank and in this case only a small portion of the tank may be visible in one FOV. In either case it is important that the inspector have a good record of what he/she has looked at.

Insulation defects will appear as patches on the tank surface when the tank is viewed using a thermal imager -- if the inspection conditions are good.

2.6 Thermal Protection and Thermal Insulation

This manual is intended to assist inspectors in finding deficiencies in steel jacketed insulation systems. There are two basic types of jacketed insulation systems.

- thermal protection systems
- thermal insulation systems

2.6.1 Thermal protection

Thermal protection systems were designed to protect certain tanks from accidental fire exposure. They include insulation materials that can withstand high temperature as would be expected in a pool fire. The systems of interest in this manual typically consist of a 13 mm layer of ceramic wool insulation blanket covered by a 3 mm steel jacket.

Common degradation modes for this insulation are:

- crushing between tank and jacket
- gaps between blankets
- tearing and drop down of blanket
- wetting by weather or product

2.6.2 Thermal insulation

Thermal insulation is generally designed to insulate the tank contents from the ambient surroundings. Some insulation systems must also act as thermal protection systems against fire impingement and therefore must include some high temperature insulation.

The systems of interest in this manual typically consist of 102 mm of insulation covered by a 3 mm steel jacket.

The 102 mm insulation may consist of various insulation types. Examples are:

- a 51 mm layer of fibreglass insulation over a 51 mm ceramic wool insulation blanket covered by a 3 mm steel jacket (this system would also meet the thermal protection requirement)
- plastic foam
- all fibreglass

Common degradation modes for this insulation are:

- crushing between tank and jacket
- gaps between blankets
- tearing and drop down of blanket
- wetting by weather or product

2.7 Detection of Insulation Deficiencies

Insulation deficiencies will be detectable only if there is a temperature gradient from the inside to the outside of the tank. Laboratory testing has shown that gross deficiencies (i.e. insulation is not present in spots) can be detected for both 13 mm and 102 mm insulation thicknesses provided there is a temperature difference between the lading and the surroundings of at least 5-10°C. Table 2-1 summarizes the deficiencies that can be detected.

Table 2-1: Insulation Deficiency Detection

Type of Deficiency	Detectable with Small Temperature Gradient (5-10°C)	Detectable with Large Temperature Gradient >10°C
areas of no insulation	yes	yes
crushed insulation	maybe	yes
wet insulation	yes	yes
insulation separated from tank wall	no	no
insulation separated from jacket	no	no

3. Inspection

The inspection involves observing a tank using a thermal imager. Based on the image obtained it may be possible to identify insulation deficiencies, which will appear as unusual patches on the tank surface in the thermal image.

Tanks can be inspected under two basic conditions, small thermal gradient (i.e. natural ambient conditions) or with large thermal gradient (i.e. with heat/cold sources, e.g. steam or solar heating). The best method by far is to use large thermal gradients that can be easily identified by a thermal imager. With smaller gradients it may be more difficult to interpret the images.

3.1 Inspection with Large Thermal Gradients

In this method the tank to be inspected is heated/cooled from within relative to the surroundings, or the sun is present and external heating is significant.

3.1.1 Solar Heating

If the tank exterior is heated by the sun and if the lading is cool then this should result in good inspection conditions. With solar heating and cool lading the insulation deficiencies will appear as cool spots on the tank surface (i.e. the cool interior tends to cool the steel jacket if insulation is not present). Please note that tank colour plays an important role here. Also note that if the lading is warm or hot then solar heating may reduce the contrast and degrade the inspection.

The following points should be remembered if the inspection is conducted with solar heating:

- shadows will look cool and may be interpreted as deficiencies
- solar angle affects the amount of heating
- white lettering will heat up less than a dark tank-car, etc.
- glossy surfaces reflect more than dull surfaces

Solar reflection will always work against an inspection, because this reflected energy has nothing to do with the tank insulation.

The following additional comments are given for guidance.

For uninsulated tanks, solar heating will cause the vapour space wall to heat up more than the liquid wetted wall, allowing the imager to identify the liquid level.

Solar heating with shadows will result in thermal images with patterns similar to the visual image of the tank and therefore this effect can be identified when comparing thermal to visual images of the inspected tank.

The equilibrium temperature of the tank surface will vary around the tank due to the varying sun impingement angle on the tank surface. The tank top will get hotter than the tank bottom with the sun high in the sky, etc.

For tests where solar heating is needed to generate a thermal gradient the following conditions are needed to obtain good results:

- sun should be behind the thermal imager (imager should not be looking into the sun)
- the suns rays should be perpendicular to the tank surface (i.e. tank broad side to the sun).
- if the tank is not perpendicular then the sun should be high in the sky to get good solar heating.

If the tank is solar heated, a 10-15°C difference is necessary between the solar heated surface and the unheated surface for the insulation deficiencies to show clearly.

3.1.2 Hot/Cold Lading

In some cases the lading might be very warm or cool relative to ambient and this can be used to obtain good inspection results. This can be done purely for inspection purposes or it may be part of normal tank filling/emptying operation. Examples of normal operation may include:

- tanks being emptied by pressurization with hot vapours
- tanks with steam injection to preheat lading for ease of removal
- tanks being filled with lading at high or low temperature relative to ambient

For the case of heating purely for inspection, the tank would be emptied and a hot gas (air or steam) would be circulated through the tank until an adequate thermal image can be obtained. This method is currently used (e.g. PROCOR) for some new tanks as required by some clients. This technique could be used during routine inspections. If this approach is used then it should be noted that the steam or hot air should flow for at least one hour before the inspection is conducted, to establish the temperature gradients.

3.2 Inspection with Small Thermal Gradients

In this method the tank is inspected with no artificial sources of heat. The method relies on thermal gradients that are present naturally due to day-night temperature cycles.

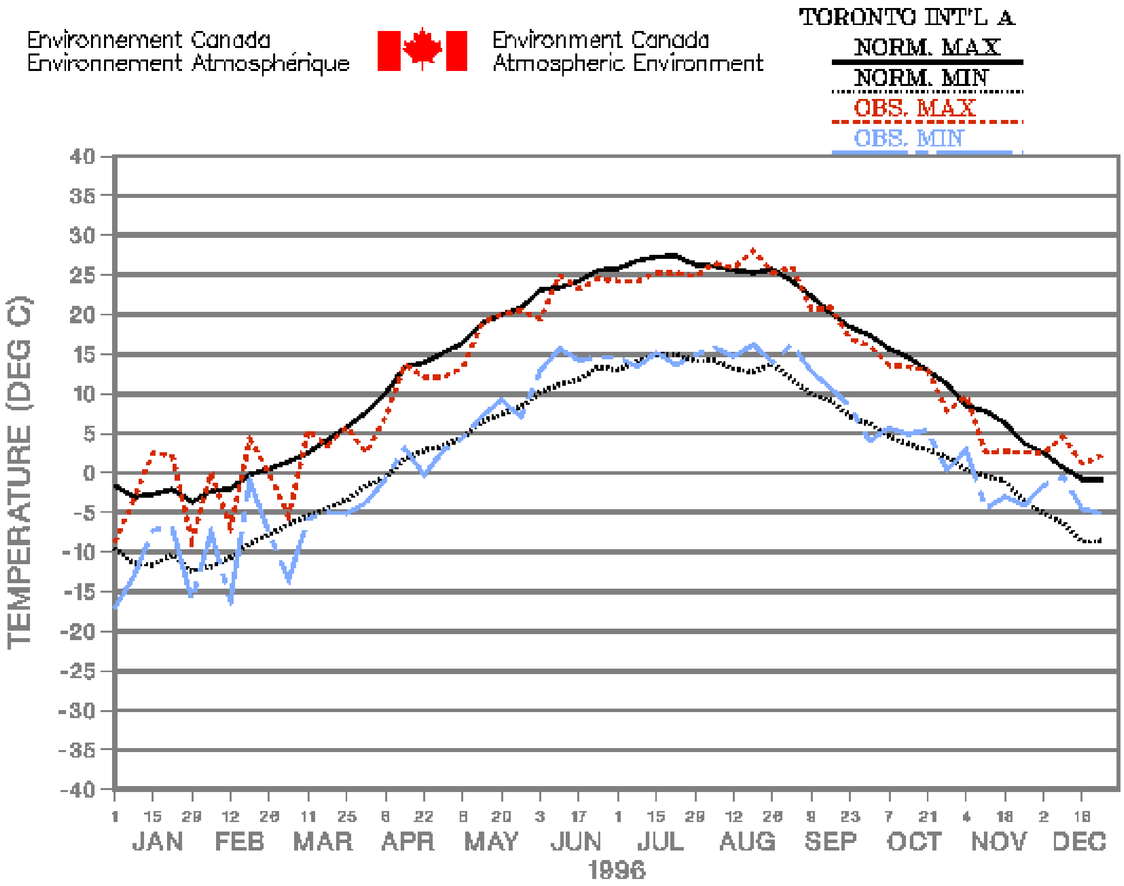

Figure 3-1: Weekly average minimum and maximum temperatures at Toronto, 1996 (Environment Canada).

3.2.1 Normal Ambient Temperature

For good inspection the lading temperature must be at least 5°C different than the ambient temperature. The larger the difference, the better the inspection. For normal day-night temperature cycles the tank lading will be at or near the average of the normal high and normal low daily temperature. The greatest difference between the lading and ambient temperature will be about half the difference between the daily maximum and minimum. Figure 3-1, presenting the normal day and night temperatures in Toronto, clearly shows that the daily variations in temperature (approximately 10°C) will lead to gradients that can be used for inspection purposes. Sudden extreme changes in temperature can also be used to improve inspection resolution.

3.3 Poor Inspections

With thermography it is possible to have poor inspections. The inspections depend on the conditions of the tank and the surroundings. During an inspection it is possible to have false positives (indications of insulation deficiencies that are not real) and false negatives (missed insulation deficiencies).

False positives can be caused by several factors including:

- reflection of thermal radiation from the ground, sky, sun, nearby structures
- variations in tank surface finish or colour
- variations in heat transfer on the tank surface
- remnants from the thermal imager

These false images complicate the interpretation of imagery and must be considered very carefully. Most effects that can cause false indications can be identified in visual images of the tank. Therefore it is very important that thermal imagery be viewed along with identical visual images (i.e. photographs or video).

For variations in heat transfer, sometimes this is visible in video images. For example, snow, ice, dripping hot/cold water etc. will cause local contrast on a thermal image.

False negatives are possible if the thermal gradients are not sufficient for the inspection. This is more difficult to identify. In some cases it can be determined by taking a few surface temperature measurements.

3.4 Inspection Validation

It is very important that the inspector find a way to validate a given inspection. By using visual inspection along with the thermography it is usually possible to eliminate false positives. However, it is more difficult to eliminate false negatives. If the inspection cannot be validated then it is very possible that the inspection may have missed insulation deficiencies.

As a validation consideration, if you are inspecting a line of tanks with the thermal imager and you see absolutely nothing on the tanks (no spacers, etc.) then it is very likely that the inspection is invalid. Even with new tanks, with perfect insulation it is usually possible to see the steel jacket spacers if there is a good thermal gradient. If you see nothing then the thermal gradient is probably very small.

If in a line of tanks, one tank is identified as bad, then it – MAY – validate that the others are good. However, this assumes that all 10 tanks have the same fill history, and this may not be true. Keep in mind that the thermal gradients may vary from tank to tank. The thermal gradients depend on when the tank was filled, what the filling temperature was, the fill level, etc.

As a general rule if you see absolutely nothing on a tank using the thermal imager then assume the test is invalid unless you can prove that a good thermal gradient is present.

4. Hardware and Software

The hardware consists of the following:

- thermal imager with video output or image capture and storage capability
- tripods for holding cameras steady
- VHS or other video recorder
- video camera (recommended) or still camera for visual image recording
- PC computer with video capture card
- image analysis software

Figure 4-1 schematically shows the connections between the hardware components. During the field inspection, the use of a laptop is optional, but a VCR should be used to record the output from the thermal imager.

It is also recommended that the inspector have a hand held temperature probe to obtain surface temperatures.

For this manual it has been assumed the inspector has a thermal imager such as the Texas Instrument NightSight or TI Palm IR 250 with no image capture capability. Therefore the inspector must capture images directly to the PC or record them on the VCR for later transfer to the PC for analysis.

4.1 Recording Images on VCR

For each thermal image taken, 30 seconds of steady video should be recorded on a VCR (VHS or 8 mm). This duration will be adequate for future frame capturing with a computer or video printing. Using frame averaging to reduce image noise (applies to TI Nightsight only) requires that the same field of view be held for the duration of the recording. To maintain the same field of view, the camera should be roof mounted on a vehicle or mounted on a tripod. It is recommended that the thermal images be recorded on a VCR even when capturing images directly with a PC to provide a hard copy back-up.

4.2 Image Capture to PC

Image capturing is generally only required when image enhancement is needed to allow insulation deficiencies to be identified. This may be the case if an imager with low resolution is used (i.e. TI NightSight) or the temperature gradients on the surface are very small. If the temperature gradients are large or a high resolution imager is used (TI Palm IR 250) the deficiencies can usually be identified directly from video prints of the recorded image. This eliminates the capture -- enhancement steps, significantly reducing the amount of work required for the analysis.

Capturing an image onto a PC can be done real-time while the tank car is being thermally imaged or later from the recorded images. The following technique applies to both cases.

The following procedure assumes the use of a SNAPPY capture card, but with minor modifications would apply to any capture card.

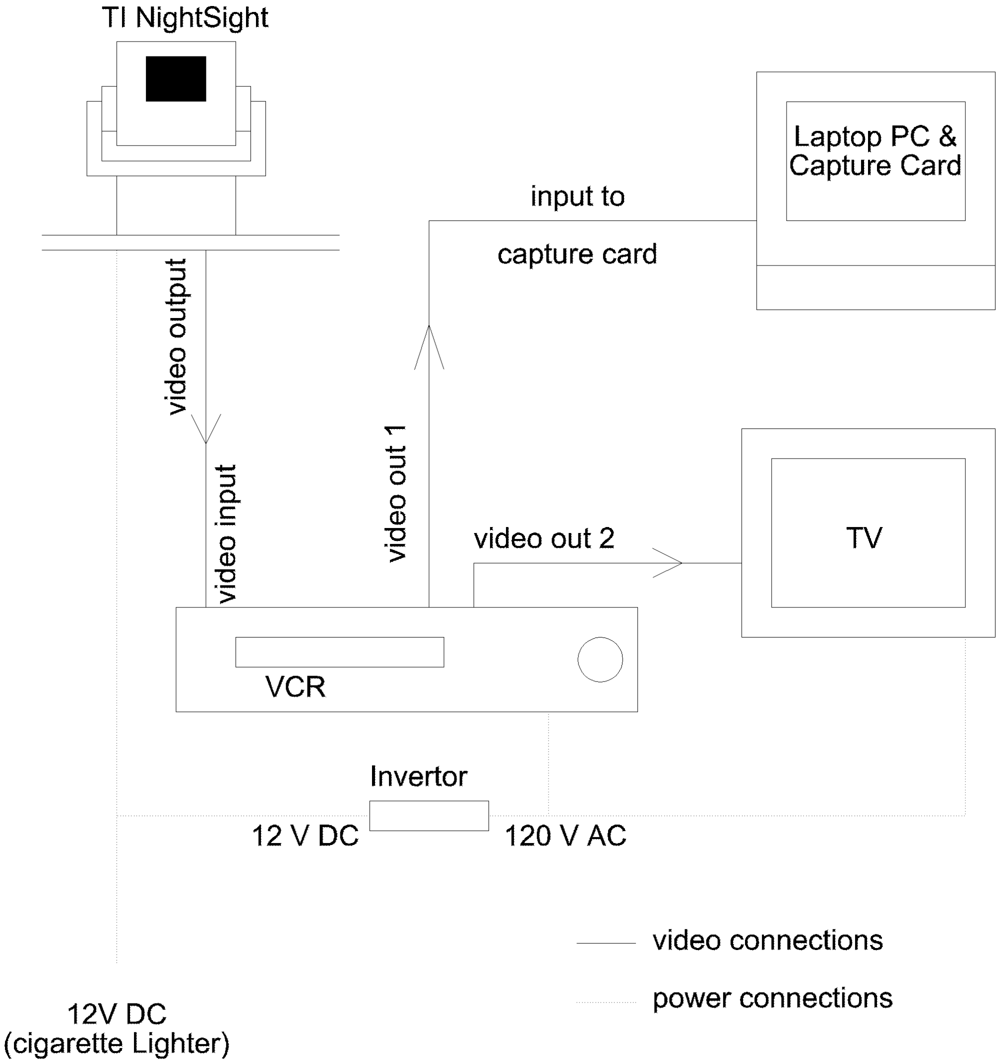

Figure 4-1: Schematic of equipment connections

Equipment

- **SNAPPY Video Snapshot** by Play Technologies Inc. capture card. This is an external capture card that connects to a PC parallel port. It captures still images composed of one, two, four, or eight averaged video frames.
- PC with parallel port (486 or higher recommended)
- **Image Tool** image processing software (requires Windows 95) available as shareware from http://ddsdx.uthscsa.edu/dig/itdesc.html; or equivalent

Procedure

1. Configure the **SNAPPY** software with :

video source :	live camera
picture quality :	highest quality still scene (each capture image is an average of 8 video frames)
picture type :	black and white

2. Using the **SNAPPY** software :
    a) click on **Snap** to capture image
    b) click on **Save** to save image to disk. All images should be saved in TIFF format.
3. repeat a) and b) to capture a total of 4* images.
4. Using **Image Tool**:
    a) in the **Stack** menu choose **new**
    b) in the **File** menu choose **open** and open the four files created in steps 1 and 2. This will load the files into the stack.
    c) in the **Stack** menu choose **close**
    d) in the **Processing** menu choose **stacks : stack averaging**. This will produce a new window containing the average of the images in the stack
    e) in the **File** menu choose **save** and save the new window to disk.

* more or fewer images may need to be averaged to give a good image depending on the quality of the original image

4.3 Image Enhancement

The frame averaged image saved in step 4 above can be enhanced by performing a histogram stretch. This enhancement may be necessary for images from the TI Nightsight.

To perform a histogram stretch, in **Image Tool**:

1. In the **file** menu choose **open** and open the file to be enhanced, or if already open make the image window active.
2. In the **Settings** menu choose **preferences** and confirm that on the **stretch** menu the **interactive** box is checked.
3. In the **Processing** menu choose **interactive histogram stretch**.

4. In the following dialogue box use the sliders to choose the grey scale range of interest that best enhances the image and press save. This will generate a new window with the enhanced image.
5. In the **File** menu choose **save** and save the enhanced image in the new window.

4.4 Hardware Limitations

The TI NightSight used in this test program suffered from a constant false image of alternating light and dark curving bands. When viewing very small temperature gradients (of order 1°C) these bands are of the same order as the thermal gradients being viewed. This same pattern can be seen in the TI Palm IR 250 but to a lesser extent.

These bands can be partly removed using the following procedure:

1. Place a surface of uniform temperature in front of the imager so that it fills the complete field of view and save an averaged image following the procedure of Section 4.2. Generally saving one false image per imaging session will be sufficient.
2. Using **Image Tool**:
    a) In the **File** menu choose **open** and open the false image and image to be enhanced.
    b) In the **Processing** menu choose **quantitative subtraction**
    c) In the following dialogue box choose the actual image as **image 1** and the false image as **image 2**, press OK. A new window will appear with the false image subtracted from the real image.
    d) In the **File** menu choose **save** and save the image in the new window.

5. General Inspection Procedure

The following general procedure is suggested. Field experience should be used to update this procedure as necessary.

1. Select tank to be inspected and position thermal imager and video/still camera to view desired parts of tank. Generally the tank will have to be viewed from three positions: both sides and top. Depending on the field of view of the imager and the distance between the imager and the tank, 2-4 images will be required for each view. For adequate resolution, no more than about half the tank car should fill the field of view, otherwise move closer to the tank car. If more than four images are required to cover the complete tank car it will be difficult to analyse the insulation over the entire tank car. In this case the imager should be moved farther from the tank car. The imager should be placed normal to the direction of the tank axis.

2. Record ambient conditions including:

    - date, time, location, view direction (compass heading).
    - air temperature (current and previous day/night)
    - wind conditions (no wind, light wind strong wind, etc.)
    - weather conditions (rain, etc.)
    - solar conditions (clear sunny, overcast, etc.)
    - note any important factors (such as sudden drop in temperature from previous day, etc.)

3. Record tank condition as completely as possible:

    - tank number, built date, converted date, inspected date, tank type, location, etc.
    - paint colour, condition (gloss, flat, dirty, wet, oily, etc.)
    - note damage, recent repairs, patches, etc.
    - lading type and temperature
    - fill level
    - selected surface temperatures

4. Survey the area around the tank to look for other sources of thermal radiation including:

    - position of sun, moon (compass heading and elevation angle).
    - sky condition (clear, overcast, etc.)
    - ground condition (hot asphalt, gravel, grass, snow or ice, etc.)
    - nearby hot pipes, lighting fixtures, exhaust stacks, flames, etc.

Note: Uninsulated tank parts in contact with the liquid lading will give an indication of the lading temperature. If these uninsulated tank parts are at a significantly different temperature than the insulation steel jacket then this may be an indication that a large thermal gradient exists and this suggests a good test sample.

5. Obtain images of the tank using both a thermal imager and video/still camera. The FOV of the video camera should be adjusted so that it is the same as that of the thermal imager.

It is recommended that the remaining steps be completed at a later date in an office environment. Only the raw data needs to be collected in the field.

6. If the images are of very low contrast, capture frames and enhance the image as outlined in Sections 4.2 and 4.3. If the images are clear, they can be viewed directly from the video recording. It is recommended that hard copies of thermal images of deficient tanks be made for future reference (i.e. by using a video printer).

7. Compare thermal image to visual image to correlate image details. Look for thermal image contrast that correlates with:

    - variations in surface finish
    - new/old patches of paint
    - lettering, signs, etc.
    - rusted areas
    - snow
    - wet/oily areas
    - different colours of paint (white tank with black lettering, etc.)
    - areas shaded from the sun
    - bottom half of tank (reflecting ground) vs top half of tank (reflecting sky)

8. Are there significant areas of different contrast in thermal image that cannot be explained by details in visual image?

    - if no, and the technique can be validated (Section 3.4), then the tank probably does not have insulation deficiencies
    - if yes, then contrast may be due to the following:
        a) thermal insulation deficiencies (no insulation)
        b) wet insulation
        c) crushed insulation
        d) uninsulated parts

Thermographic inspection flow charts for both ambient conditions and heating/cooling of the lading are presented in Figure 5-1 and Figure 5-2 respectively. A sample data sheet for recording tank data during the inspection is included in Appendix A. The schematic of the tank is intended to be used to note the position of any surface defects on the tank car.

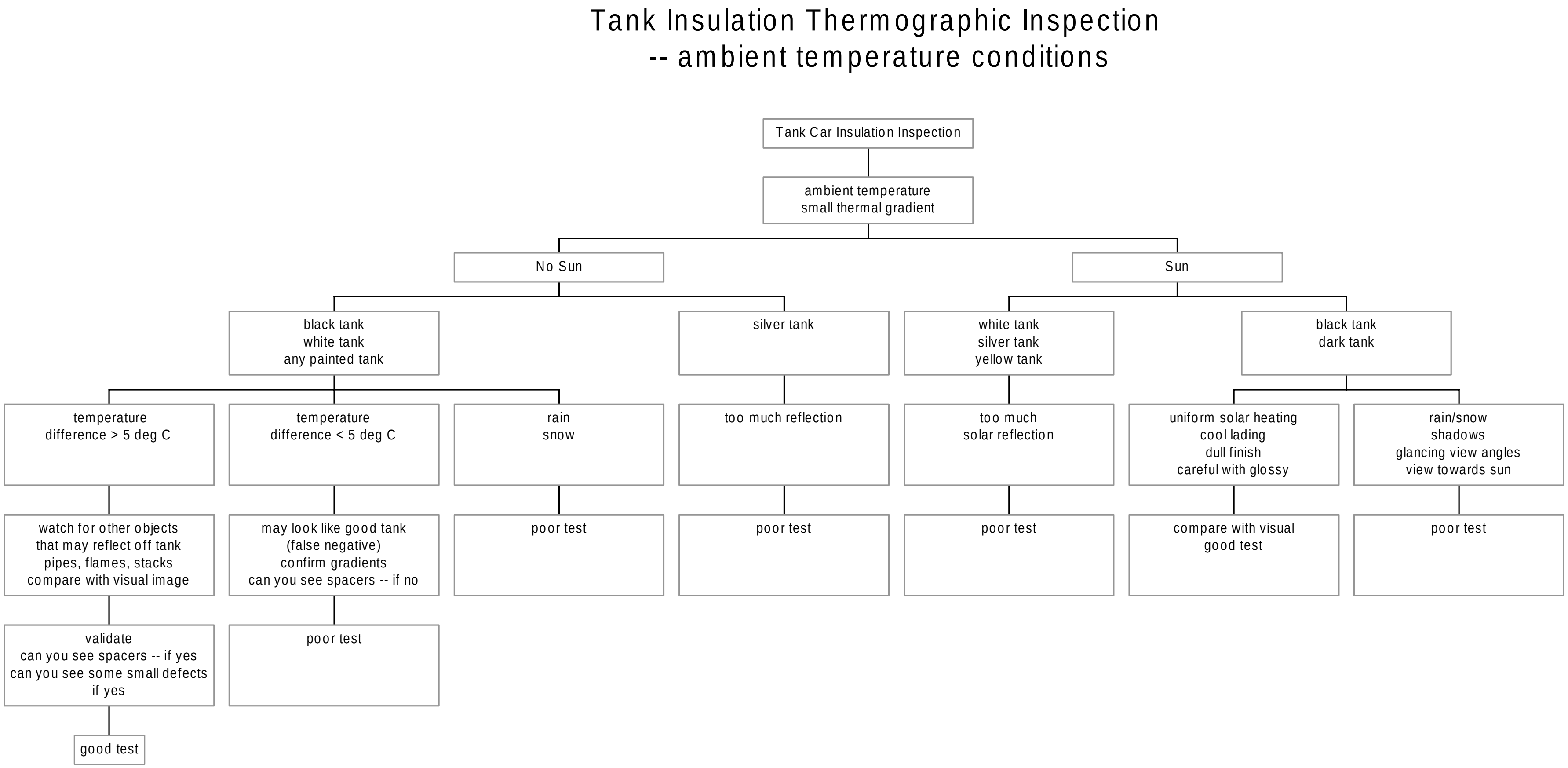

Figure 5-1: Thermographic inspection flow chart for ambient conditions

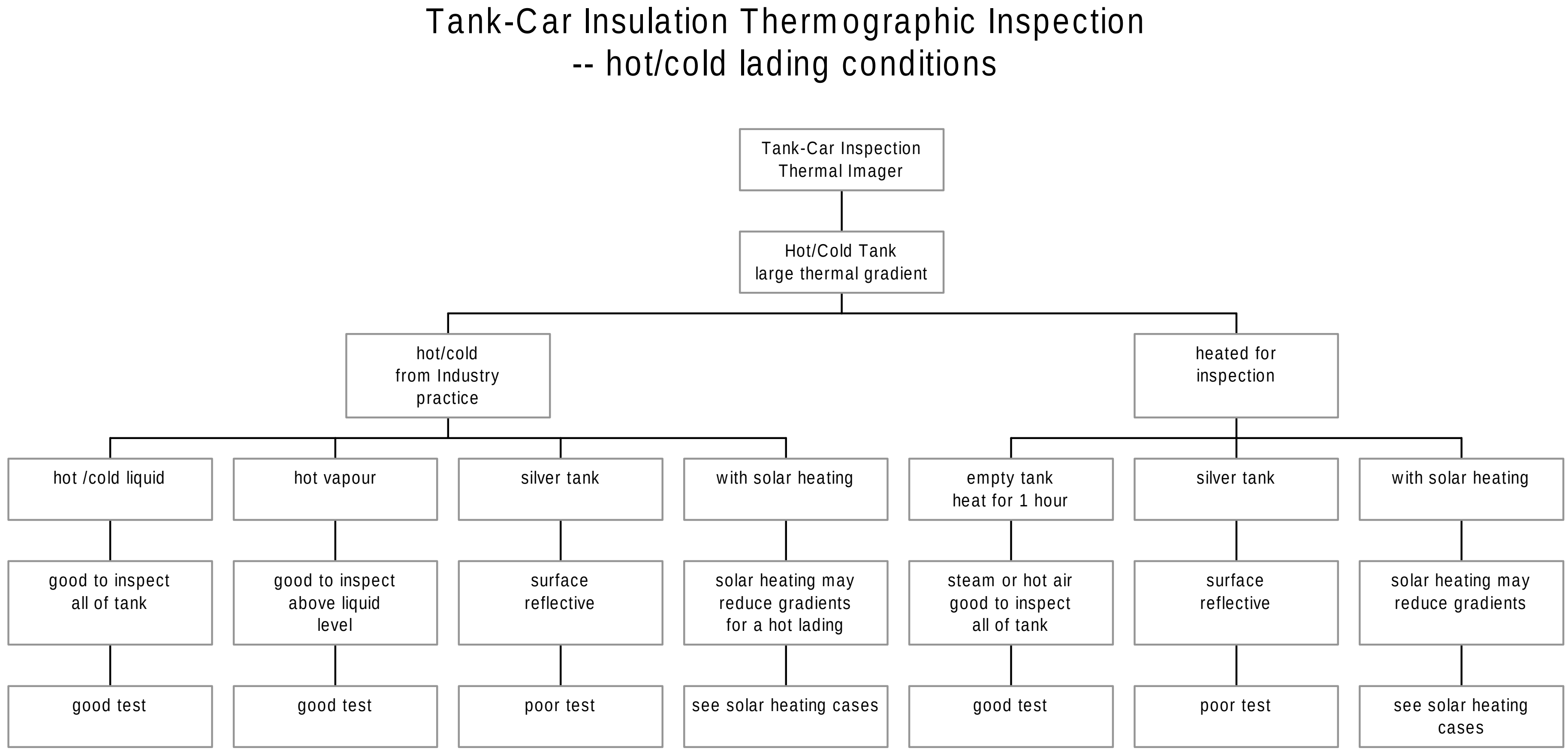

Figure 5-2: Thermographic inspection flow chart for large gradients

6. Defect Assessment

An infinite number of possible defect combinations exist and therefore it is necessary to simplify the problem for the purpose of defect assessment. Figure 6-1 shows a sample tank with a number of identified insulation defects of various shapes and sizes.

Defects should be organized by size, orientation (shape) and proximity. Although defect location is important (i.e. defects in vapour space are most important), we must consider low defects just as important as high defects because of the possibility of tank rollover in an accident.

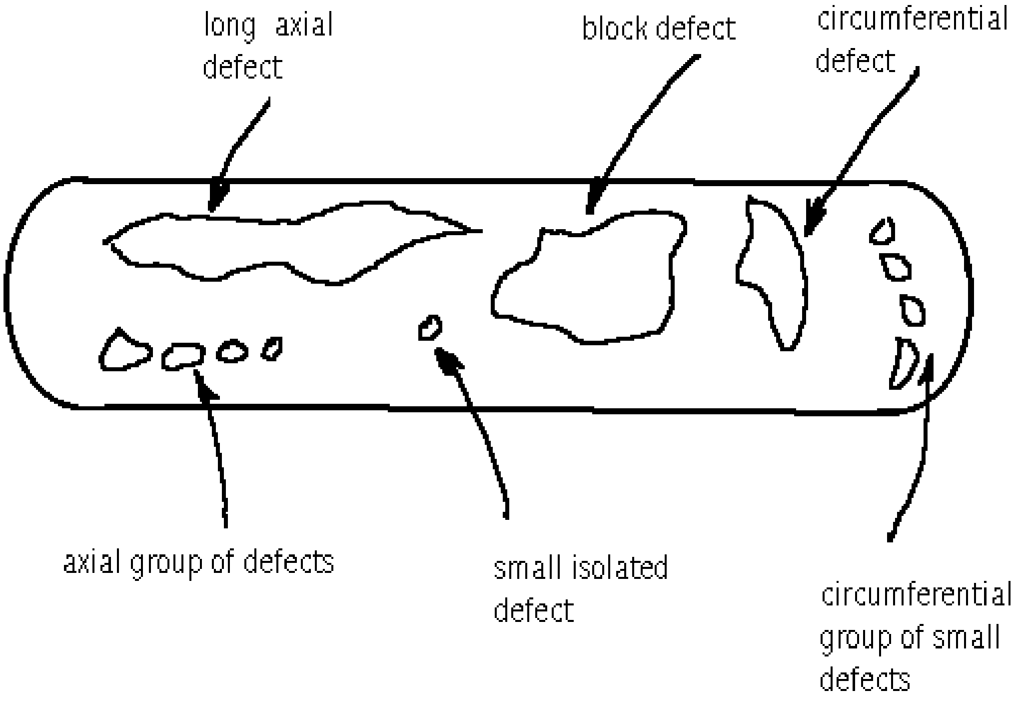

Figure 6-1: Sketch of Tank with Multiple Defects

6.1 Defect Size

The defect size affects both heat transfer and structural considerations.

6.1.1 Defect Size and Heat Transfer

If a defect is small then the surrounding protected material will tend to cool the defect area by conduction if the tank is exposed to fire. As the defect size increases, there comes a point where further increase in size does not change the defect area temperature. If several small defects are close together, then they may act as one large defect.

It should also be noted that a small defect is less likely to be exposed to fire.

A heat transfer analysis (see Birk and Cunningham (1999)) showed that:

i) When an isolated defect minimum dimension exceeds about 0.4 m the size no longer affects the temperature that is achieved in the defect. This means that all defects over a certain size have similar temperatures. This then means that only the shape and orientation of the defect matters.

ii) For long axial defects, the width does not matter if it exceeds 0.2 m.

iii) For long circumferential defects, the width does not matter if it exceeds 0.2 m.

iv) When defects are separated by less than 0.5 m they are effectively part of the same defect.

6.1.2 Defect Size and Stress

The following is based on a preliminary finite element analysis of an isolated defect (see Birk and Cunningham (1999) for details).

The stresses in a small defect may be lower than in a large defect because the surrounding protected material may take on more of the load as the small defect expands due to heating. However, this is not the case with defects that run the full length of the tank or the full circumference.

Basic structural considerations allow us to make the following conclusions:

- For the same area, long axial defects and long circumferential defects are worse than a block defect.

- For a tank with many defects, the net effect must consider all the defects together (i.e. one large defect is the same as many small defects close together).

6.1.3 Defect Size Classification

Table 6-1 gives some guidance on how to classify the size of a defect.

Table 6-1: Guidance on Defect Size (isolated block defects)

defect maximum dimension (m)	**type**	**significance**	**note**
L < 0.1	very small	not very, unless there are many of these close together	i) probably at limit of what can be detected by imager, ii) temperature significantly reduced by surrounding protected material
0.1 < L < 0.4	small	moderate	temperature reduced by surrounding material
0.4 < L < 1	intermediate	very	little benefit from surrounding material
L >1	large	very	no protection from surrounding material

Note: for long strip defects the critical defect size should be multiplied by 0.5 (i.e. small defect < 0.2 m).

6.2 Defect Orientation and Shape

Defect orientation and shape should be noted as:

- axial
- circumferential
- diagonal
- block

A long axial defect is very dangerous because if heated it could undermine the entire tank structure (i.e. it may act as a zipper!). Similarly a long circumferential defect can cause major structural concerns (tub rocket?).

A long diagonal defect should be seen as both a long axial and long circumferential.

A block defect may also be very significant depending on its size and location.

The only other possible defect would be a long diagonal defect such as shown in Figure 6-2. This type of defect should be analysed as both axial and circumferential

6.3 Defect Proximity

If defects are well separated then they should be considered as separate. However, if defects are close together then they act as a single defect and the protected material between them should be considered as part of the defect.

Analysis suggests that defects less than 0.5 m apart should be considered as a single defect.

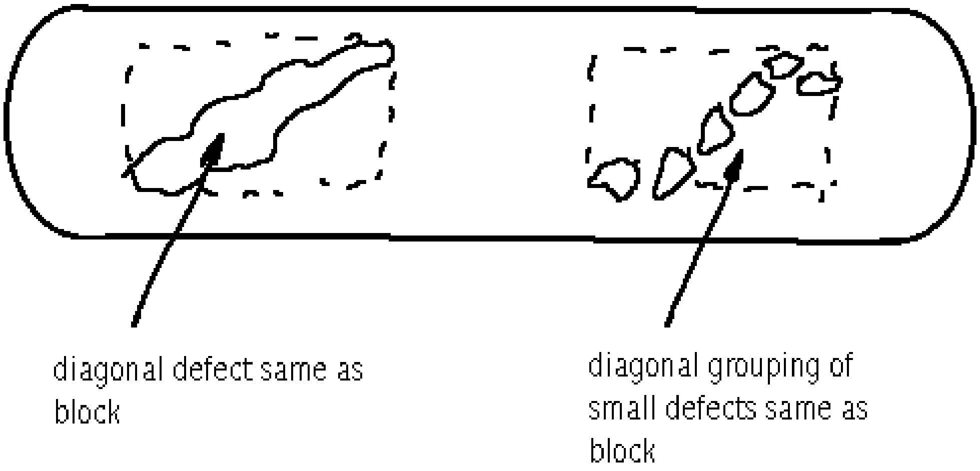

Figure 6-2: Sketch Showing Diagonal Defects

6.4 Defect Impact on Tank

For thermally insulated tanks, insulation defects cause an increase in the overall heat transfer to/from the lading.

For thermally protected tanks, defects reduce the survivability of the tank in a fire.

Computer model analysis of a thermally protected tank (see Birk and Cunningham (1999)) exposed to pool and torch fires resulted in the following conclusions about how insulation defects affect the response of a tank to fire impingement.

Fill Effect

Insulation defects allow more heat to enter the tank from a fire. This added heat flow boils off more liquid and causes a tank to empty its contents faster through its PRV. As the tank empties, the liquid level drops and more of the tank surface is left uncooled by the liquid. The wall temperature in the vapour space can become very high and this can lead to tank failure.

Heat will enter the tank most effectively when defects are below the liquid level (i.e. defects in liquid space, or lower sections of the tank).

PRV effect

If a PRV is sized for an insulated tank and if the tank is uninsulated the PRV may not have sufficient flow capacity. This could result in higher pressures in the tank and early failure.

Wall Temperature Effect

As the liquid empties out of the tank, more of the tank wall is exposed to vapour from within the tank. The vapour is not effective at cooling the tank wall and if this part of the wall is exposed to fire, very high wall temperatures can result.

Defects in the vapour space will result in higher wall temperatures in the vapour space and this will lead to accelerated weakening of the tank.

Burst Strength Effect

As the steel gets hotter in the defective area the tank material begins to degrade and lose its strength. As the temperature gets higher and higher the material is more prone to high temperature creep effects so that lower stresses are needed to rupture the tank. Even if the PRV is working properly the tank may fail.

7. Defect Pass/Fail

The pass/fail criteria are different for thermally protected tanks (112 type) and thermally insulated tanks (105 and 111 type). Some tanks may have to be assessed under both criteria.

7.1 Thermal Protection

The requirement for thermal protection systems for pressure tank-cars is specified in CGSB 79.18:

thermal protection on a tank car, shall have sufficient thermal resistance so that there will be no release of any lading from within the tank car, except release through the pressure relief device, when subjected to:

> *(1) A pool fire for 100 min, and*
> *(2) A torch fire for 30 min.*

Thermal protection systems considered in this report include:

- thermal protection only, consisting of 13 mm of ceramic blanket insulation covered by a 3 mm steel jacket
- thermal insulation and thermal protection system, consisting of 51 mm of ceramic blanket, 51 mm of fibreglass insulation and 3 mm of steel jacket

Based on computer simulations using AFFTAC (see Johnson (1998)) current thermal protection and insulation systems provide more than enough protection to save a tank from 100 minutes of pool fire exposure or 30 minutes of torch exposure.

7.1.1 Assessment Procedure

The pass/fail criteria proposed here for defective thermal protection are based on the analysis reported by Birk and Cunningham (1999). This analysis has not been fully validated and therefore allowing any defect has risk associated with it.

The following assessment procedure is preliminary and should be used with extreme caution. Testing is needed to verify the appropriateness of the stated defect percentages. The authors of this report do not guarantee that the stated percentages of defect are safe in a real-world accident.

The following is the suggested assessment procedure:

i) The inspector should identify defects as described earlier in this manual and then determine defect type and the total percentage of tank area that is defective. If it is only possible to inspect one side of the tank, then it should be assumed that the other side is the same and the percentage calculated on this basis.

ii) Inspector should make a general assessment of the predominant defect geometry including:

- long axial defects
- long circumferential defects
- distributed small defects
- large block defect

ii) Inspector should make a judgement as to the condition of the insulation in the non-defective areas of the tank. This assessment should include:

- deformations in the steel jacket suggesting insulation crushing
- tank exterior surface condition (rough, old paint, new paint)

iii) Inspector should make an assessment of the confidence level in the inspection results, as follows:

a) high confidence
  - excellent test conditions (good temperature gradients)
  - clear indications of defects
  - clear indications of normal features such as insulation spacers
  - inspector is able to validate results

b) medium confidence
  - good test conditions
  - good indications of normal features such as insulation spacers
  - good indications of defects
  - limited validation

c) marginal or no confidence
  - poor conditions
  - no indications
  - no validation

iv) based on the above, use the following tables to determine the inspection outcome.

The suggested pass/fail criteria are based on Table 7-1. If inspection conditions are not ideal, then a suggested approach is presented in Table 7-2.

Table 7-1: Tank Insulation Defect Assessment Matrix (Preliminary)

% tank surface defective	condition	outcome	comment
0%	ideal	pass	analysis suggests that tank has very high probability of surviving a pool fire for 100 minutes (estimated FOS = 3.0) see notes 1 and 2
0 – 4% small isolated defects	excellent	pass	analysis suggests that tank has high probability of surviving engulfing pool fire for 100 minutes (est. FOS = 1.6)
> 4% long axial or long circumferential defects	poor	fail	these types of defects are more serious than isolated defects from a structural standpoint
> 10% large block defect	poor	fail	these types of defects are more serious than isolated defects from a structural standpoint
5 – 14% small isolated defects	good	pass with condition that remaining insulation must be in good condition re-inspect at next cleaning or within 12 months	analysis suggests that tank has good probability of surviving engulfing pool fire for 100 minutes (est. FOS = 1.5)
15 – 25% small isolated defects	marginal	pass with condition that remaining insulation must be in excellent condition – re-inspect at next cleaning or within 12 months	analysis suggests that tank has fair probability of surviving in engulfing pool fire for 100 minutes (est. FOS = 1.4)
> 25% small isolated defects	poor	fail	analysis suggests that tank has a significant probability of failing in engulfing pool fire after 100 minutes (est. FOS < 1.4)

FOS = factor of safety = (tank burst pressure at 100 minutes in pool fire)/tank pressure
analysis suggested that FOS = 1.6 is a reasonable target value.

Notes:

1) Assumes 112 type propane tank, 816^{o}C pool fire, tank starts 90% full from 16^{o}C, 13 mm of thermal insulation of 22.7 W/m^{2}K conductance covered by 3 mm steel jacket

2) Even with ideal insulation there is some risk that a tank will fail in an engulfing fire. All insulation defects reduce the survivability of a tank in a fire.

Table 7-2: Field Test Confidence Level Result Matrix (Preliminary)

test type and confidence level	**total defect as % of tank surface**	**inspection outcome**
field test with high confidence in results		see Table 7-1
field test with medium confidence		
	< 4%	pass if defects are long axial or long circumferential, mark for detailed evaluation at next cleaning (steam test) or re-inspect within 12 months
	< 10%	if defects are small and well separated, conditional pass, re-inspect in 12 months
	> 10%	mark for detailed evaluation at next cleaning (steam test) or re-inspect within 12 months
	> 15%	mark for immediate steam test
field test with marginal or no confidence		re-inspect at earliest opportunity
steam test		see Table 7-1

7.2 Thermally Insulated Tanks

If a pressure tank-car has thermal insulation it must meet the following requirement.

If insulation is a specification requirement, it shall be of sufficient thickness so that the thermal conductance at 15.5°C (60°F) is not more than 1.533 kJ/hr m^2 *°C (0.075 Btu/hr* ft^2 *°F) temperature differential. If exterior heaters are attached to the tank, the thickness of the insulation over each heater element may be reduced to one-half that required for the shell.*

Based on a simple heat transfer analysis, it has been concluded that current tank designs (102 mm insulation, 51 mm fibreglass, 51 mm ceramic blanket) just meet the thermal insulation requirements.

Therefore, no observable defect is allowed at this time.

8. Conclusions

A thermal imager can be used to find thermal insulation deficiencies on a tank when a thermal gradient is present. This technique applies to both thermally insulated and thermally protected tanks. The method applies to a wide range of insulation types.

Small thermal gradients are present due to natural day-night heating-cooling cycles. Large thermal gradients may be present during filling or off-loading of tanks or under solar heated conditions. Inspection can be performed on empty tanks by using heat injection (steam or hot air) techniques.

For large thermal gradient testing the results are easy to interpret – i.e. deficiencies will be obvious. For small thermal gradients, care must be taken to ensure that indications of thermal deficiencies are real and not simply reflection effects, solar effects or surface finish effects.

Insulation defects in thermal protection systems reduce the survivability of tanks in fires. The risk of tank failure in a fire increases with the size of deficiencies and the shape. Survivability of a tank with deficiencies depends on a number of factors including:

- initial fill
- PRV operating characteristics
- insulation condition and properties
- location and size of defects

Simulation results suggest that a thermal protection system with less than 4 percent defect has a good probability of surviving a pool fire for 100 minutes (as per CGSB standard).

For thermal insulation systems, deficiencies increase heat transfer between the tank lading and the surroundings. Systems consisting of 51 mm of fibre glass and 51 mm of ceramic blanket cannot have significant deficiencies and pass the current CGSB standard for thermal insulation systems.

The pass/fail criteria proposed in this manual for defective thermal protection are based on the analysis reported by Birk and Cunningham (1999). This analysis has not been fully validated and therefore allowing any defect involves risk.

This assessment procedure is preliminary and should be used with extreme caution. Testing is needed to verify the appropriateness of the stated defect percentages. The authors of this report will not guarantee that the stated percentages of defect are safe in a real-world accident.

9. References

Johnson, M. R., Tank Car Thermal Analysis, Volume 1, User's Manual for Analysis Program, DOT/FRA/ORD-98/09A, Nov. 1998

Johnson, M. R., Tank Car Thermal Analysis, Volume 2, Technical Documentation Report for Analysis Program, DOT/FRA/ORD-98/09B, Nov. 1998

Birk, A. M., Cunningham, M. H., Thermographic Inspection of Tank-Car Thermal Insulation, Transportation Development Centre, TP 13203E, 1998

Birk, A. M., Cunningham, M. H., Tank-Car Insulation Defect Assessment Criteria: Part 1: Thermal Analysis of Defects, Transportation Development Centre, TP 13518E, 1999

Appendix A

Sample Tank Data Sheet

Tank Car Field Survey - Field Results

Test : _________ Date : ___________ Time : ____________________

Weather

Same as Previous ☐ Sunny ☐ Overcast ☐ % Cloud____ Rain ☐ Amb. T. _____°C

Tank Car

Number : ______________________________ Build date : ______________________________

Model : ______________________________ Convert Date : ___________________________

Dual diameter : ☐ Test Date : ______________________________

Commodity : ___________________________

Surface Conditions

Colour :	Finish :		Sun reflection :
White ☐	Glossy ☐	Wet ☐	Entire side ☐
Black ☐	Flat ☐	Oil ☐	None ☐
Other ___________	Patched ☐	Dust ☐	Fraction : _________
	Rust ☐		

Video

Thermal imaging : Visual :

Tape # : __________________ Tape # : __________________

Counter : _________________ Counter : _________________

Notes :